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BLAST PRESSURES INSIDE AND OUTSIDE
SUPPRESSIVE STRUCTURES

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**BLAST PRESSURES INSIDE AND OUTSIDE
SUPPRESSIVE STRUCTURES**

by
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December 1975

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SUMMARY

Suppressive structures are designed to remain intact under blast loads from internal explosions and are intended to attenuate the blast waves which emanate from them. Therefore, reasonable estimates must be made of short and long duration internal blast loads in these vented structures, and of the degree of blast attenuation for various vent panel designs.

This report covers past analytical and experimental studies in explosion venting, and summarizes much of the recent blast loading work in the suppressive structures program. Scaling laws are briefly reviewed, as is the concept of an effective vent area ratio. Curve fits to external blast overpressures and impulses are given for a variety of vent panel designs, including nested angles, perforated plates, zeos, louvres, and interlocking I-beams.

Internal blast loads consist of initial and several subsequent reflected shocks, followed by a much longer blowdown or quasi-static pressure. Curves are given for prediction of the initial reflected wave overpressure and impulse. Theories for the blowdown phase are discussed, followed by presentation of curves for scaled peak blowdown pressure and duration. A computer code for prediction of intrapanel pressures during the blowdown phase is described.

This report is a reprint of a paper given at the 46th Shock and Vibration Symposium, San Diego, California, October 1975.

PREFACE

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BLAST PRESSURES INSIDE AND OUTSIDE SUPPRESSIVE STRUCTURES

I. INTRODUCTION

Hazards produced by accidental explosions within facilities that contain and process high explosives have concerned safety engineers for many years. The most obvious way to reduce the hazards is to separate such facilities as far apart as possible to avoid the potential for propagation of an explosion. Another method is to use partial confinement walls and cubicles to direct and control the output from an accidental explosion. To further reduce the required spacing between high explosives facilities the U.S. Army under its plant modernization program is developing uniformly vented suppressive structures which will significantly reduce or suppress the external blast overpressures, the fragment hazard and the thermal effects. The suppressive structures tested to date have been rectangular enclosures consisting of a main frame with multilayered vented panels making up the sides and roof. The technology for vented suppressive structures has not yet reached the stage where the design is a straightforward process. Consequently, development programs supported by the Edgewood Arsenal are being conducted to develop this technology so that suppressive structures can be routinely applied to explosive processing operations to better protect personnel and adjoining facilities while reducing the safety distance required between them.

The loading from an explosive charge detonated within a vented or unvented structure consists of two almost distinct phases. The first phase is that of reflected blast loading. It consists of the initial high pressure, short duration reflected wave, plus perhaps several later reflected pulses arriving at times closely approximated by twice the average time of arrival at the chamber walls. These later pulses are attenuated in amplitude because of irreversible thermodynamic process, and they may be very complex in waveform because of the complexity of the reflection process within the structure, whether vented or unvented. If the structure has solid walls, the blast loading can be estimated by using sources of compiled blast data for normally reflected blast pressures and impulses such as References 1 and 2, and the well-known Hopkinson's blast scaling law (see Chapter 3 of Reference 3). The effect of vented areas in the suppressive structures on reduction of the reflected blast loading can be very complex, and will not be addressed in detail in this paper.

As the blast waves reflect and re-reflect within the structure and as unburned detonation products combine with the available oxygen, a quasi-static or gas pressure rise occurs and the second phase of loading takes place. Measurements of this pressure rise and its duration have been made by various investigators prior to the suppressive structures program using chambers having a single opening for venting. Work has also been conducted to develop a theory for predicting time histories of pressures in vented structures. However, from the present program, data are now also available from structures uniformly vented through the sides and roof. From all of the above data one obtains the answer that for the particular ratios of vent area to chamber volume tested, the venting has no effect on the peak quasi-static pressure. Thus, peak quasi-static

pressures for unvented or poorly vented structures are the same. Unfortunately, essentially no data exist for quasi-static pressures within well-vented structures and the crucial question of the actual maximum gas pressure rise within such chambers remains unanswered. We must at present use the unvented pressure rise for design purposes. An important point that needs to be made is that, although quasi-static pressure measurements have been made in various vented and unvented structures, the determination of the peak value is subject to interpretation because the reflected pressures are also present on the data records. Because suppressive structures consist of multi-layered walls, how the quasi-static pressure loads each layer is also of interest to the designer. At this time no data are available for these intrapanel pressures. However as part of this program a computer program has been developed to predict these pressures. When experimental data become available, its accuracy can be assessed.

In addition to determining the reflected blast loading and the quasi-static gas pressure rise and decay which are needed in designing these structures, the amount of venting required to reduce the blast pressures outside to a desired level must be estimated. Using limited data, Baker et al⁴ generated a method of correlating emitted blast waves from suppressive structures and comparing them to free-field blast data to determine the degree of blast attenuation. Since a suppressive structure is made up of several vented layers, this method introduced an effective vent area ratio, α_e , which can be computed for a variety of combinations of vented elements in a suppressive structure. In References 5 and 6, more and better blast pressure data are now available and we have updated the equations for predicting the reduction in overpressure over a considerable range of distances outside the structure. Also, good external side-on impulse measurements were made by Schumacher and Ewing⁵ so that the reduction in impulse can also be predicted.

II. SCALING

A. Blast Waves

The scaling of properties of blast waves from various explosive sources is a common procedure and most blast data are reported in scaled parameters from the Hopkinson-Cranz or Sachs' scaling laws. These laws, and others used in blast technology, are derived and discussed in detail in Chapter 3 of Reference 3. Blast waves from explosions in the open are affected by weight W (or total energy) of the explosive, distance R from the center of the explosive, geometry and energy density of the explosive source, and ambient atmospheric conditions such as pressure p_o and sound velocity a_o . For charges of different total energy but same type and geometry detonated under the same ambient conditions, the Hopkinson-Cranz scaling law applies. It predicts³ that side-on or reflected overpressures, and scaled side-on or reflected impulses, are functions of Hopkinson-scaled distance, i.e.,

$$P_s = f_1 (R/W^{1/3})$$

$$P_r = f_2 (R/W^{1/3})$$

$$\begin{aligned}(i_s/W^{1/3}) &= f_3 (R/W^{1/3}) \\ (i_r/W^{1/3}) &= f_4 (R/W^{1/3})\end{aligned}\tag{1}$$

(If ambient conditions differ between one experiment or analysis and another, another scaling law must apply. The law usually used in this case is Sachs' Law³).

Suppressive structures are intended to attenuate the blast waves from accidental explosions by reflecting the initial waves striking their inner surfaces, and venting the gas pressures behind the shock fronts at a relatively slow rate. In attempting to scale the properties of the waves emanating from these structures, one must include parameters which describe the geometry and venting characteristics of the structure as well as the conventional scaled distance. A scaling law including these additional parameters was postulated by Baker, et al⁴ and is as follows:

$$\begin{aligned}P_s &= f_5 (R/W^{1/3}, X/R, \alpha_e) \\ (i_s/W^{1/3}) &= f_6 (R/W^{1/3}, X/R, \alpha_e)\end{aligned}\tag{2}$$

The new parameters in this law are a characteristic length X of the suppressive structure, and an effective vent area ratio α_e . Model and prototype structures are assumed to be geometrically similar for exact scaling, but the characteristic length X can be thought of as the square root of the wall area of interest or the cube root of the structure's internal volume V , for the law to apply in at least an approximate manner. The definition of α_e will be discussed in the next section of the paper. Also inherent in the law are the same assumptions inherent in Hopkinson scaling, i.e., no change in ambient conditions, explosive type or geometry. Heat transfer to the suppressive structure is also not considered in the development of the scaling law. The scaling law, of course, does not specify the actual functions f_5 and f_6 . These will be treated later in the paper.

B. Quasi-static Pressures

As the blast waves from explosions within suppressive structures reflect and re-reflect, and as the energy available from the explosive source is added to the air within the structure, long-term pressures can build up within the structure. These pressures are termed "quasi-static pressures" because they can last long enough to apply essentially static internal gas pressure loads to the structure.* Some data existed for pressures within vented chambers prior to the suppressive structures program⁷⁻⁹, and some analyses of blowdown pressures had also been made^{7, 10, 11}. To compare such data and also to collate data being generated in suppressive structures testing, Baker, et al⁴ conducted a model analysis of the explosion venting process. The resulting scaling law has been somewhat modified in Reference 12, and is:

*With large vent areas, these pressures can conceivably vent quickly enough that venting times are comparable to structural response periods. In this case, the term "quasi-static" is inappropriate. Perhaps "blowdown or gas pressure" is a more appropriate term.

$$\left(\frac{P}{p_o}\right) = f_6 \left[\left(\frac{\alpha_e A_s}{V^{1/2/3}}\right), \left(\frac{P_1}{p_o}\right), \left(\frac{ta_o}{V^{1/3}}\right), \gamma \right] \quad (3)$$

Based on a theoretical analysis of chamber venting by Owczarek^{12,13} the scaled pressure $\bar{P} = (P/p_o)$ is a function of γ and a new scaled time

$$\bar{\tau} = \bar{A}\bar{t} = \left(\frac{\alpha_e A_s}{V^{2/3}}\right) \left(\frac{ta_o}{V^{1/3}}\right) \quad (4)$$

Here, P is absolute pressure at any time t , A_s is internal surface area of the structure, P_1 is maximum (initial) absolute quasi-static pressure, and γ is ratio of specific heat for the gases within the structure. An alternate form of Equation (3) is then

$$\bar{P} = f_7(\bar{P}_1, \bar{\tau}, \gamma) \quad (3a)$$

The initial pressure \bar{P}_1 for structures with no venting or small venting can be shown to be related^{4,7,8,11} to another scaling term,

$$\bar{P}_1 = f_8(E/P_o V) \quad (5)$$

where E is a measure of total energy released by the explosion. For tests with explosives of the same type and no change in ambient conditions, a dimensional equivalent of (5) is:

$$P_1 = f_9(W/V) \quad (5a)$$

where W is charge weight (lb) and V is chamber volume (ft³)

III. VENT AREA RATIO

From the model analysis used to develop the functional expression for the side-on over-pressure outside the structure it is obvious that the only parameter which lacks exact definition for a multi-layer, uniformly vented enclosure is α_e . For a single layer structure the vent area ratio is the vent area divided by the total area of the wall. For a multi-layer wall, however, we assumed that⁴

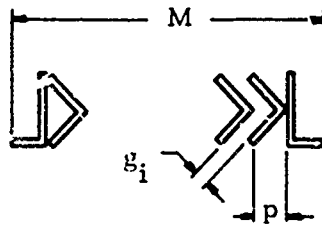
$$\frac{1}{\alpha_e} = \sum_{i=1}^N \frac{1}{\alpha_i} \quad (6)$$

This relationship has at the moment no theoretical proof. However it does reach the appropriate limits for large and small number of plates, and provides a relative measure of venting for a variety of panel configurations. Unfortunately no external pressure data currently exist for a one-layer structure with equal openings on all sides and roof. Consequently, we have established as our base line the α_e computed for a series of perforated plates using Equation 6 where the vent area ratio for each layer is simply

$$\alpha_1 = \frac{\text{Vent Area}}{\text{Wall Area}}, \alpha_2 = \frac{A_{v2}}{A_w}, \dots \quad (7)$$

For other wall elements such as angles, louvers, zeos, and I-beams used in suppressive structures the meaning of Equation 7 is less obvious. In obtaining a reasonable curve fit to the data the definition for α_e for these type of elements are as shown in Figure 1. For nested angles which have approximately one opening per projected length (see Figure 1) the data indicate that they are about twice as efficient as a perforated plate in breaking up the side-on peak pressure as it vents. For closer nested angles such that there are about two openings per projected length the angles seem to be four times as efficient as a comparable perforated plate. However, angles which are side by side and zeos seem to be as efficient as a perforated plate. Louvers seem to be more efficient than perforated plates by a factor of two. On the other hand, using the open areas as shown in Figure 1, interlocking I-beams appear to be only half as efficient as perforated plates. Note that for a uniformly vented structure the α_e of the structure is exactly equal that of a wall since the walls and roof all have the same vented area ratio. Thus in computing α_e the area of the floor is not used. Furthermore since we are interested in comparing to free field data in which the charge would still have the floor as reflecting surface the area of the floor should not be used in computing α_e .

The peak gas pressure is in general, a function of the charge weight, volume of the container, and the vent area. However, the data in Reference 8 indicates that for low vent area to volume ratios the peak pressure does not depend on this ratio. The duration does depend on the vent area ratio and, as in the case of the external pressure, a definition of α_e is required. Prior to the suppressive structures program, all the experimental data on quasi-static pressures and durations was from cubicles with a portion or all of a wall or roof missing. For these cases the vent area is the area of the opening and which the definition of α_e satisfies the scaling law is the ratio of this open area to the total interior area of the container. However, for a multi-layer suppressive structure, α_e has to be defined. Because some data are available for the one-opening cubicles, the results from the suppressive structures can be compared to them to obtain an equivalent α_e . The duration of the quasi-static pressure is a function of the peak-pressure which is sometimes difficult to interpret and the α_e will of course vary accordingly. However, if the quasi-static pressure from the multi-layer test structure is read in a fashion similar to the data from the one-opening cubicles, a comparison can be made. As will be shown later, (see Figure 10), the peak pressure was defined by drawing a smooth curve through the mean amplitude of the oscillations and extrapolating back to about the end of the second reflection which is still considered part of the reflected pressure loading. This also accounts to a certain extent for the small increment of time that is required for the quasi-static pressure to build up within the enclosure. With this maximum pressure, the duration time as read from the records and the volume of the structure, the only other parameter required to plot the uniformly vented data is a value of α_e . For the structures using I-beams, if one uses the α_e as computed for the external pressure data fits to determine the effective vent area, the quasi-static pressure data compares reasonably well with the one-opening cubicle data. For the structure using perforated plates alone and in combination with angles, if the external pressure α_e is multiplied by two the quasi-static pressure data also compares well with the one-opening cubicle data. Thus



$$A_{\text{vent}} = \ell \sum_{i=1}^n g_i / N$$

ℓ = length of element

p = projected length of angle

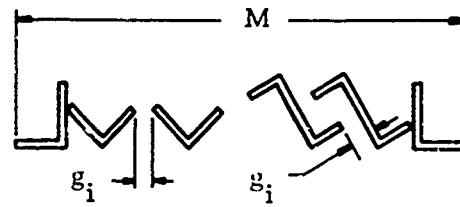
N = 2 or 4 (see text)

$A_{\text{wall}} = LM$

L = length of wall

$\alpha = A_{\text{vent}} / A_{\text{wall}}$

(a) NESTED ANGLES



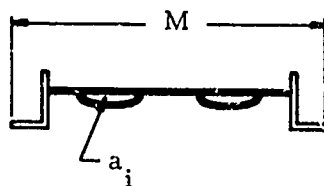
$$A_{\text{vent}} = \ell \sum_{i=1}^n g_i$$

n = number of openings

$A_{\text{wall}} = LM$

$\alpha = A_v / A_w$

(b) SIDE-BY-SIDE ANGLES OR ZEES



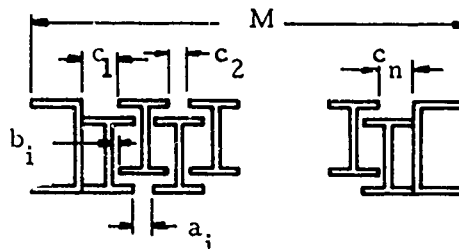
$$A_{\text{vent}} = \sum_{i=1}^n a_i / 2$$

a_i = open area of louvre

$A_{\text{wall}} = LM$

$\alpha = A_v / A_w$

(c) LOUVRES



$$A_{v1} = 2\ell \sum_{i=1}^n a_i$$

$$A_{v2} = A_{v3} = 2\ell \sum_{i=1}^n b_i$$

$$A_{v4} = 2\ell \sum_{i=1}^n c_i$$

$$\alpha_1 = A_{v1} / A_w, \dots$$

(d) INTERLOCKED I-BEAMS

FIGURE 1. DEFINITION OF EFFECTIVE AREA RATIO
FOR VARIOUS STRUCTURAL ELEMENTS

using this method for computing α_e , durations can be estimated for multi-layered, uniformly vented structures.

IV. PRESSURES OUTSIDE OF SUPPRESSIVE STRUCTURES

From the model analysis the functional expression for the side-on overpressures outside of a suppressive structure is

$$P_s = f_s(R/W^{1/3}, X/R, \alpha_e) \quad (2)$$

As shown in Reference 4, this equation is assumed to have the form

$$P_s = A(Z)^{N_1} (X/R)^{N_2} (\alpha_e)^{N_3} \quad (8)$$

Taking logarithms of both sides and making the equation linear, a least-squares curve fit can be developed using the experimental data and stating that

$$[1.0, \ln Z, \ln X/R, \ln \alpha_e] \begin{bmatrix} \ln A \\ N_1 \\ N_2 \\ N_3 \end{bmatrix} = [\ln P_s] \quad (9)$$

or substituting matrix notation

$$[L] [N] = [P], \quad (9a)$$

A least-squares fit results for the N matrix when

$$[N] = [L^T L]^{-1} [L^T] [P]. \quad (10)$$

The experimental data used to make this curve fit have been generated by the Edgewood Arsenal (EA)^{6,14,15} and the Ballistic Research Laboratories (BRL)⁵ using a variety of multi-layered vented structures. In Reference 4 a similar fit was made with the limited data that were available at that time. However, subsequently, many more measurements have been made, and better and more up-to-date curve fits are presented here. Because of the large data base now available, some of the early data have been eliminated when there was a justifiable reason. For example, over half of the early data were from a cubic structure in which one wall was changed to test different numbers of layers as well as different types of elements to obtain a variety of α_e . The other three walls and the roof remained the same throughout the tests. Measurements were then made of the side-on pressure exiting through the interchangeable wall. Thus, the structure was not uniformly vented.

The structures tested by the EA have consisted of panels of perforated plates, angles, zees and louvers. Those tested by the BRL were of basically two types. One type had

similar cross-sections as the EA structures and consisted of a series of perforated plates by themselves or plus angles. The second type of structure consisted of interlocking I-beams which had not been tested before. Table 1 lists the different types of cross-sections used and the equivalent vent area ratio computed as outlined earlier in the paper. The main problem encountered in reducing all the data to a common base was determining the relative vent area ratios, especially for the interlocking beams. Since the structures tested by the EA were of similar cross-section to the O-configurations tested by BRL, the data from these two sets of experiments were used to make the first curve fit. After some trials to obtain the relative α_r 's, the data fitted very well, as shown in Figure 2. The equation of the curve shown also fits the test results very well. The estimate of the standard deviation, S , for the experimental data about the line equals $\pm 12.7\%$. The equation can be used to predict the external side-on overpressure P_s from a similar structure at various distances or to determine the α_r required to reduce P_s to a given value at a given distance, provided the range of the experimental data is not exceeded.

The data for the interlocking I-beams were then used to determine their α_r 's so that a good curve fit to the entire data base could be made. Using the α_r 's listed in Table 1 for these three configurations, the data points from the I-beam structures were fitted by themselves and the results are shown in Figure 3. Again, the equation shown fits the data very well with $S = \pm 14.2\%$. For comparison purposes, the BRL data from the O-configurations were fitted by themselves and the results are shown in Figure 4. The equation fits the data very well with an S of $\pm 11.9\%$. Thus, the two sets of BRL data, as well as the one set obtained by the EA, correlate well within themselves.

Finally, the total experimental data base was curve fitted to obtain a general expression for P_s . The resulting equation is shown in Figure 5. The resulting value of S was $\pm 19.9\%$, slightly worse than before, but nevertheless rather good considering the great variety of cross-sections involved. Again, the limits of the pi-terms should not be violated or considerable error could result in predicting P_s or determining an α_r for a particular structure.

Since one of the primary purposes of a suppressive structure is to reduce the external side-on overpressures, the degree of reduction by a particular structure is determined by comparing the external pressure at a given distance from a charge to what it would have been without the structure, i.e., the free-field pressure. Consequently, free-field pressure data, also generated by the EA^{6,16,17,18} and the BRL⁵, have been curve-fitted in a similar fashion to the structure external pressure data to provide a free-field comparison curve. From the scaling laws, the free-field overpressure is proportional to the scaled distance, $Z = R/W^{1/3}$. However, because one portion of the data is from experiments where the charge was placed over earth while the other portion is from experiments over a concrete pad, the difference in the quality of the reflecting surface prevents direct comparison of both sets of data. Because all of the suppressive structures tested to date have a concrete floor (or equally good reflective surface), the earth data were adjusted by multiplying the charge weight used by an empirical factor of 0.62 which made the data fit the best. Within the specific limits of Z shown in Figure 6, the free-field data fit very well about the equation

TABLE I. EFFECTIVE VENT / REA RATIOS FOR
VARIOUS STRUCTURES TESTED

<u>Structure</u>	<u>Cross-Section Elements</u>	<u>α_e</u>
81 mm, Ref. 23	Zees, Perforated Plates, and Louvres.	0.025
T-1, Ref. 5	Interlocking I-beams	0.130
T-3, Ref. 5	Interlocking I-beams	0.090
T-5, Ref. 5	interlocking I-beams	0.047
O-1, Ref. 5	Nested Angles and Per- forated Plates	0.010
O-2, Ref. 5	Nested Angle and Per- forated Plates	0.011
O-3, Ref. 5	Perforated Plates	0.012
O-4, Ref. 5	Perforated Plates	0.023
Cat. V, Ref. 6	Side-by-side Angles and Perforated Plates	0.017

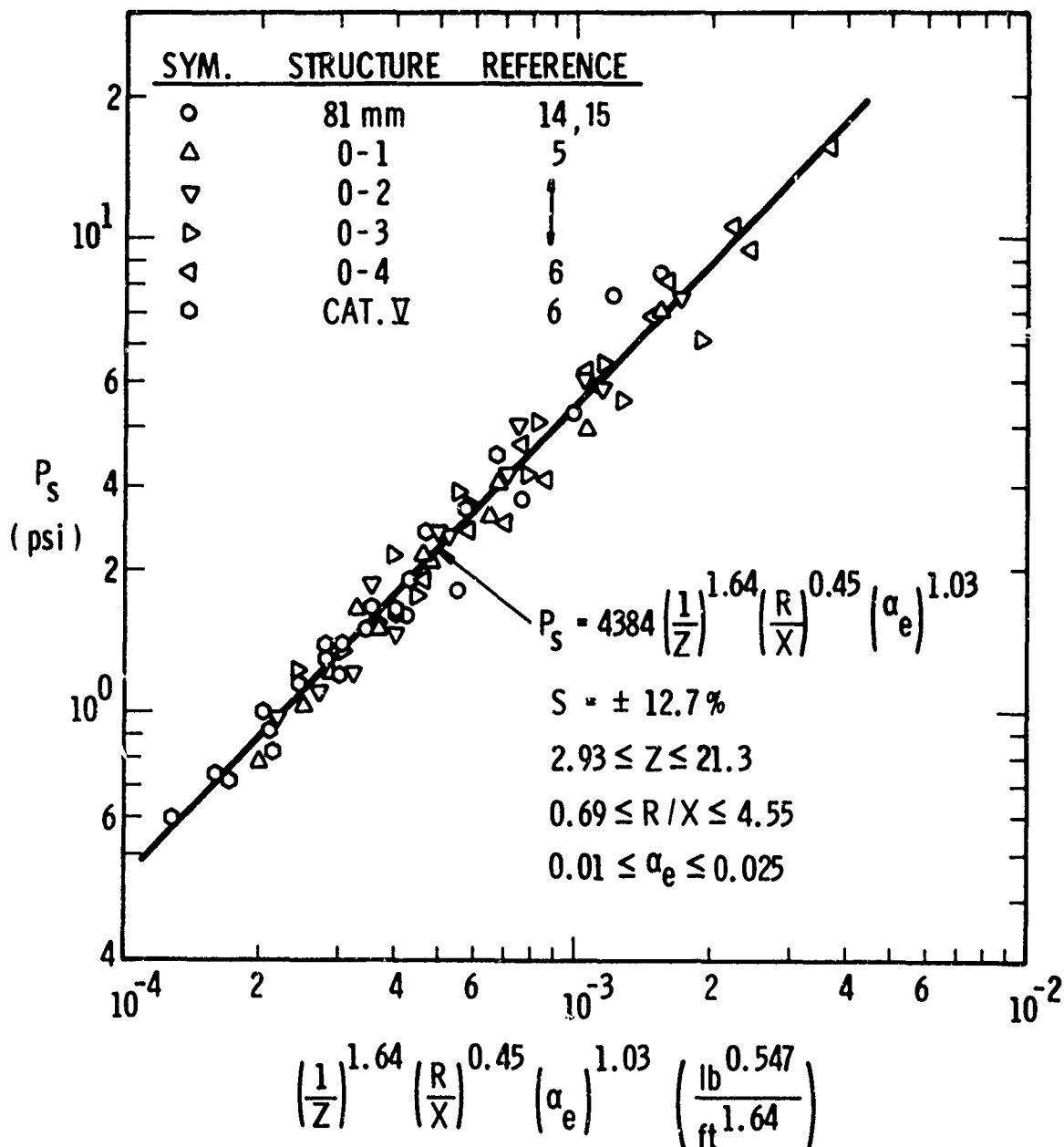


FIGURE 2. SIDE-ON PRESSURES OUTSIDE OF SUPPRESSIVE STRUCTURES USING PERFORATED PLATES, ANGLES, ZEES AND LOUVRES

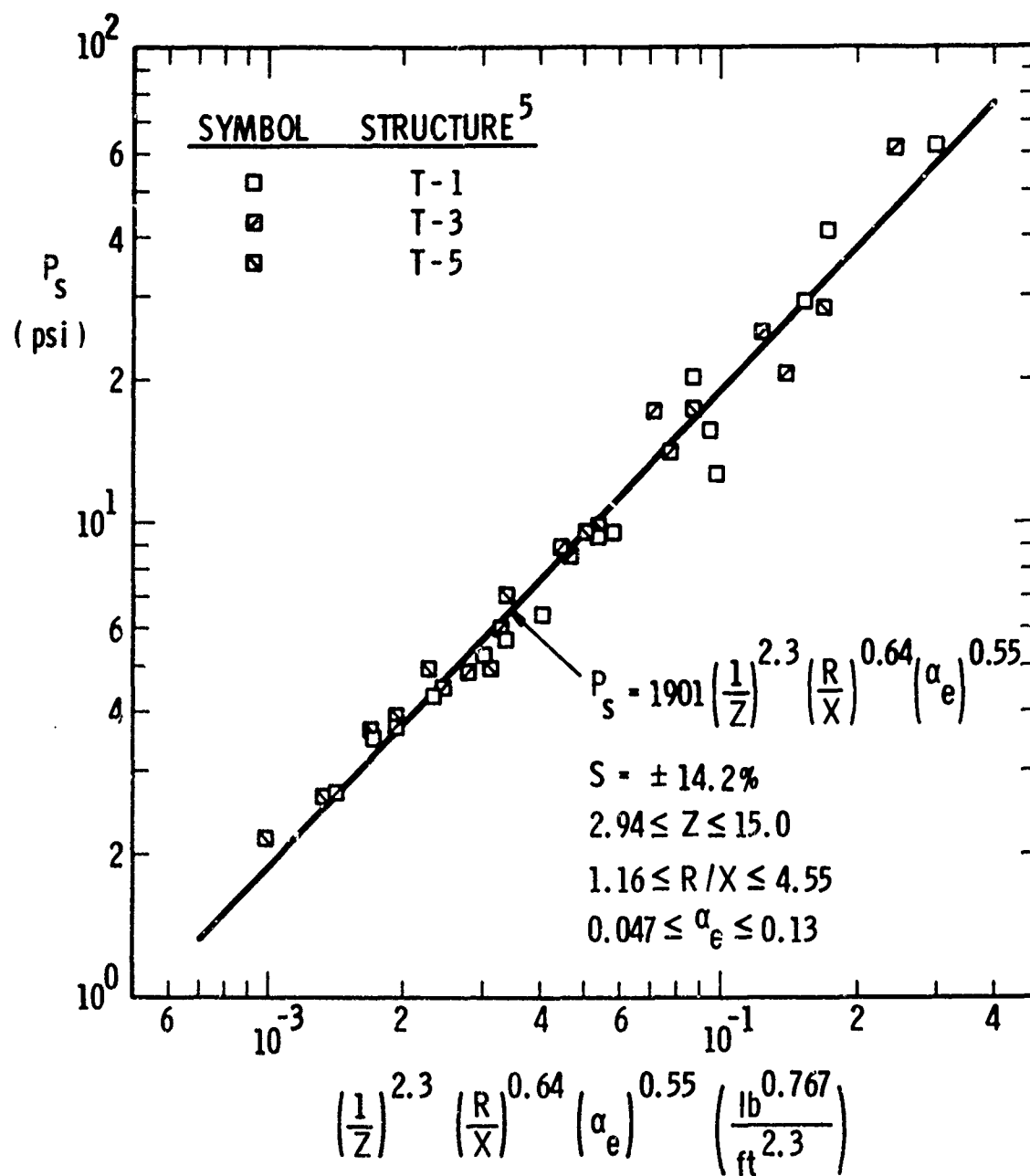


FIGURE 3 SIDE-ON PRESSURES OUTSIDE SUPPRESSIVE STRUCTURES USING INTERLOCKING I-BEAMS

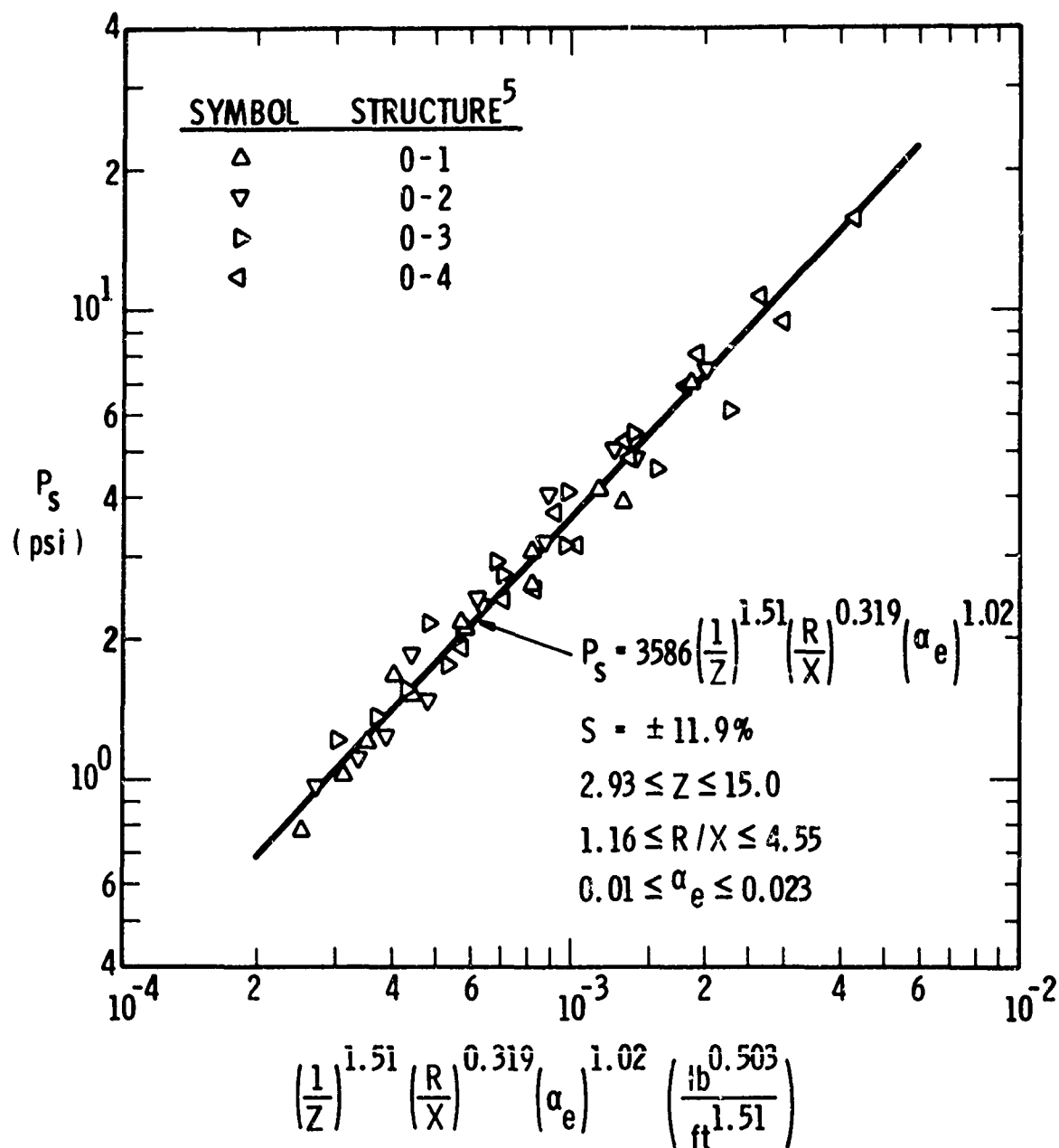


FIGURE 4. SIDE-ON PRESSURES OUTSIDE SUPPRESSIVE STRUCTURES USING NESTED ANGLES WITH/OR PERFORATED PLATES

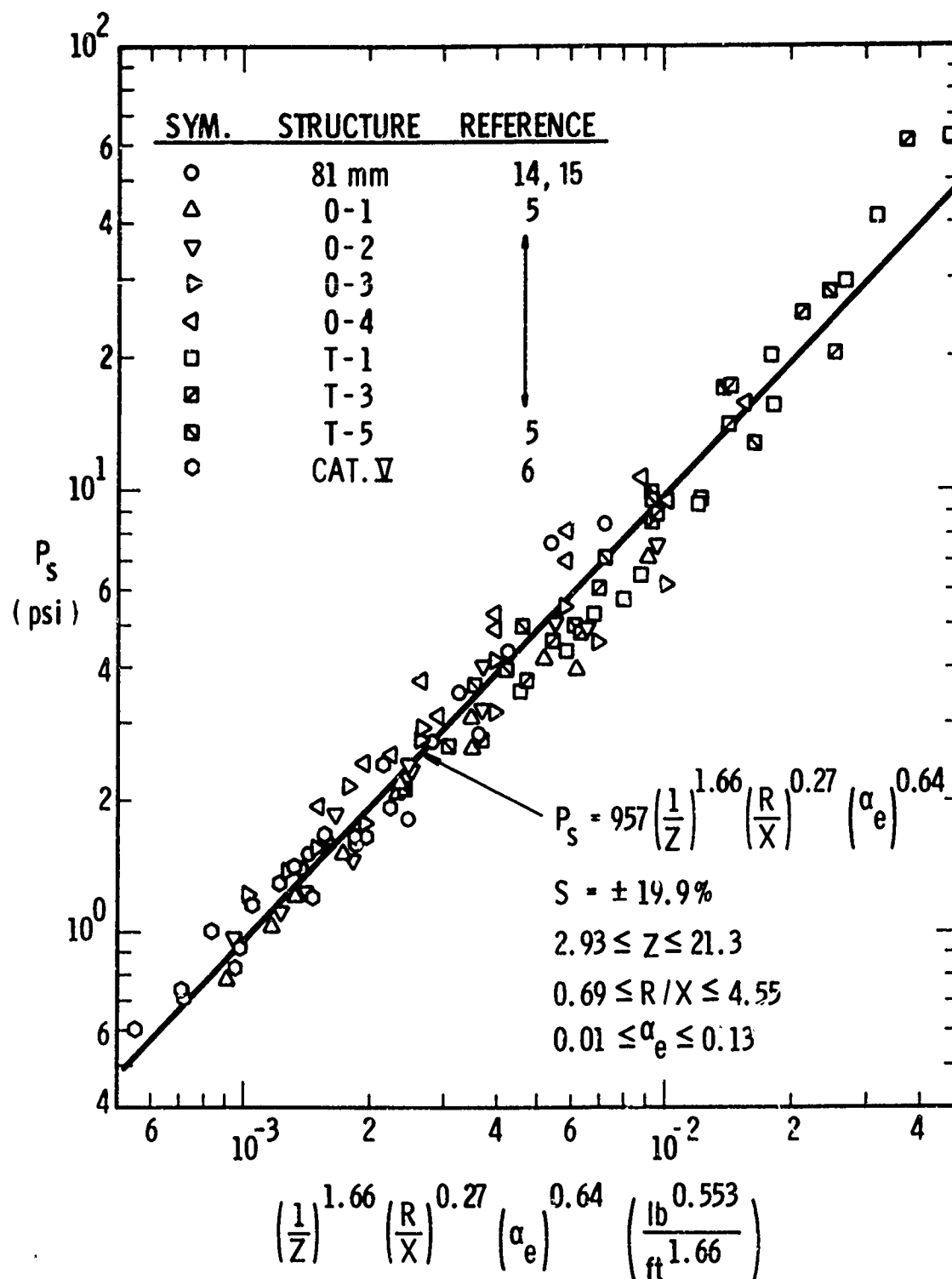


FIGURE 5. CURVE FIT TO SIDE-ON PRESSURES OUTSIDE SUPPRESSIVE STRUCTURES

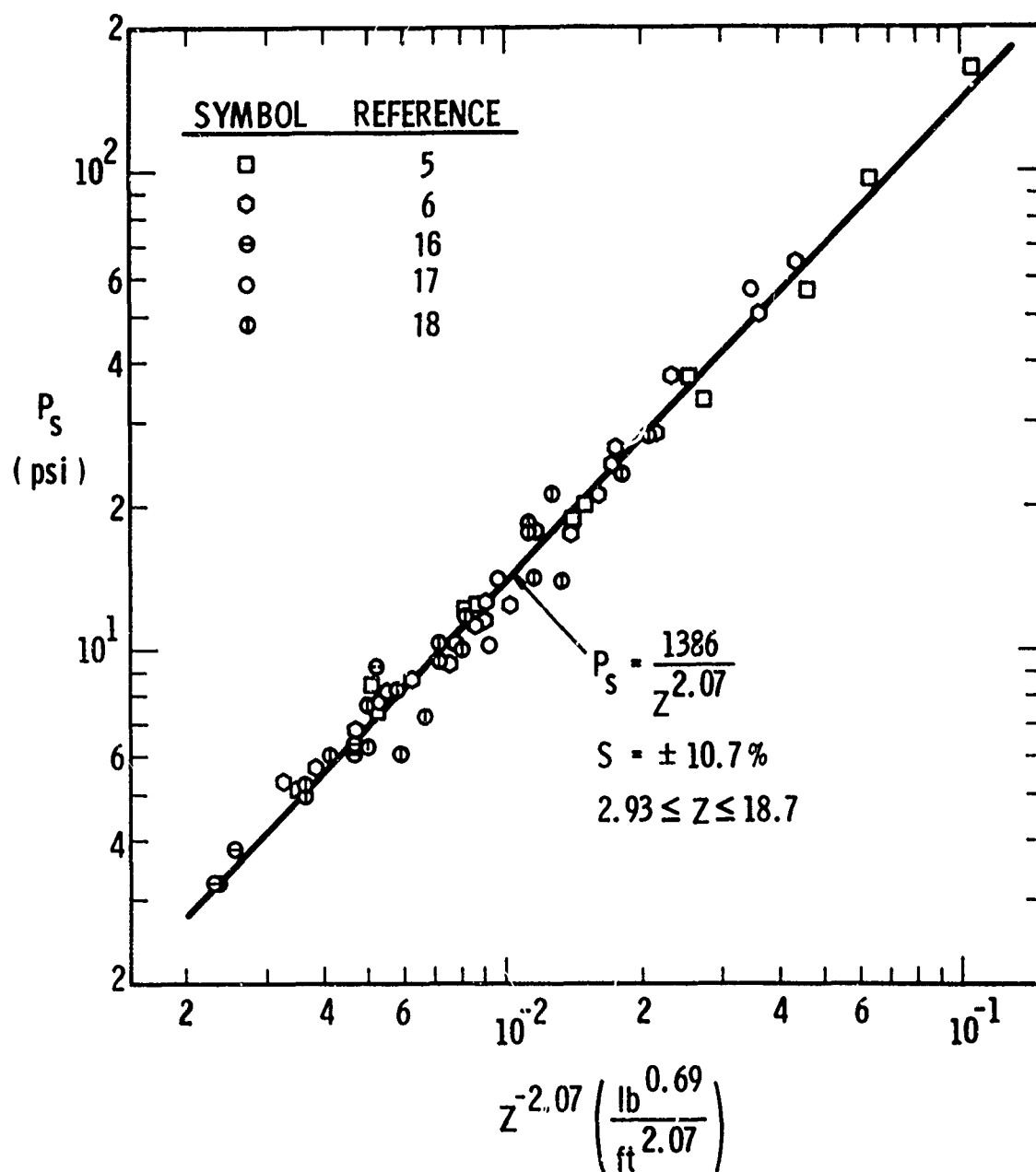


FIGURE 6. FREE-FIELD PEAK SIDE-ON BLAST PRESSURE

shown with an S of $\pm 10.7\%$. This curve then provides the free-field peak pressures at various values of Z for estimating the reduction caused by a suppressive structure.

From the experiments conducted by BRL⁵, side-on impulse was also obtained by integrating the pressure-time histories. The maximum impulses measured divided by the cube root of the explosive charge weight (scaled impulse) are reported. The scaling law for the external scaled impulse from a suppressive structure stated earlier in the paper is

$$\left(\frac{i_s}{W^{1/3}} \right) = f_6 (R/W^{1/3}, X/R, \alpha_e) \quad (2)$$

Using a similar method as for the peak pressures, the scaled impulse was curve fitted to obtain a prediction equation. Again, the only parameter which lacks an explicit definition is α_e . Using the vent area ratios derived for the peak pressure data fit as the starting point, a least-square fit was attempted. The majority of the data fitted well except for the data from the two structures which had nested angles. In these two cases the angles appeared to have attenuated the impulse more than the peak pressure compared to the perforated plate structures. If the angles were assumed to be twice as effective in reducing the impulse as was computed for the peak pressure case, the impulse data fitted very well. Thus, using the newly computed α_e 's of 0.008 and 0.010 for the O-1 and O-2 configurations, respectively, the data from the perforated plate cross-section with and without angles provide an excellent fit as shown in Figure 7. The impulse data from the I-beam structures fitted even better about the equation shown in Figure 8 with an S of $\pm 6.5\%$. Both sets of data were then used together to derive the equation shown in Figure 9. This last equation fits the data slightly worse than the two individual sets provide. However, it is as a good fit as was achieved previously with the corresponding peak side-on pressure data.

V. PRESSURES INSIDE SUPPRESSIVE STRUCTURES

When an explosion occurs within a suppressive structure, the blast wave reflects from the inner surfaces of the structure, implodes toward the center, and re-reflects one or more times. The amplitude of the re-reflected waves usually decays with each reflection, and eventually the pressure settles to a slowly decaying level, which is a function of the volume and vent area of the structure and the nature and energy release of the explosion. A typical time history of pressure¹⁹ at the wall of a suppressive structure is shown in Figure 10. The process of reflection and pressure buildup in either unvented or poorly vented structures has been recognized for some time, dating from World War II research on effects of bombs and explosives detonated within enclosures.²⁰ More recently, study of these pressures has revived because of interest in design of vented explosion chambers, and we will discuss here the recent work.

A. Reflected Pressures

The initial shock impinging on the inner surfaces of suppressive structures applies an intense loading of short duration to these surfaces. This loading is complicated by the geometry

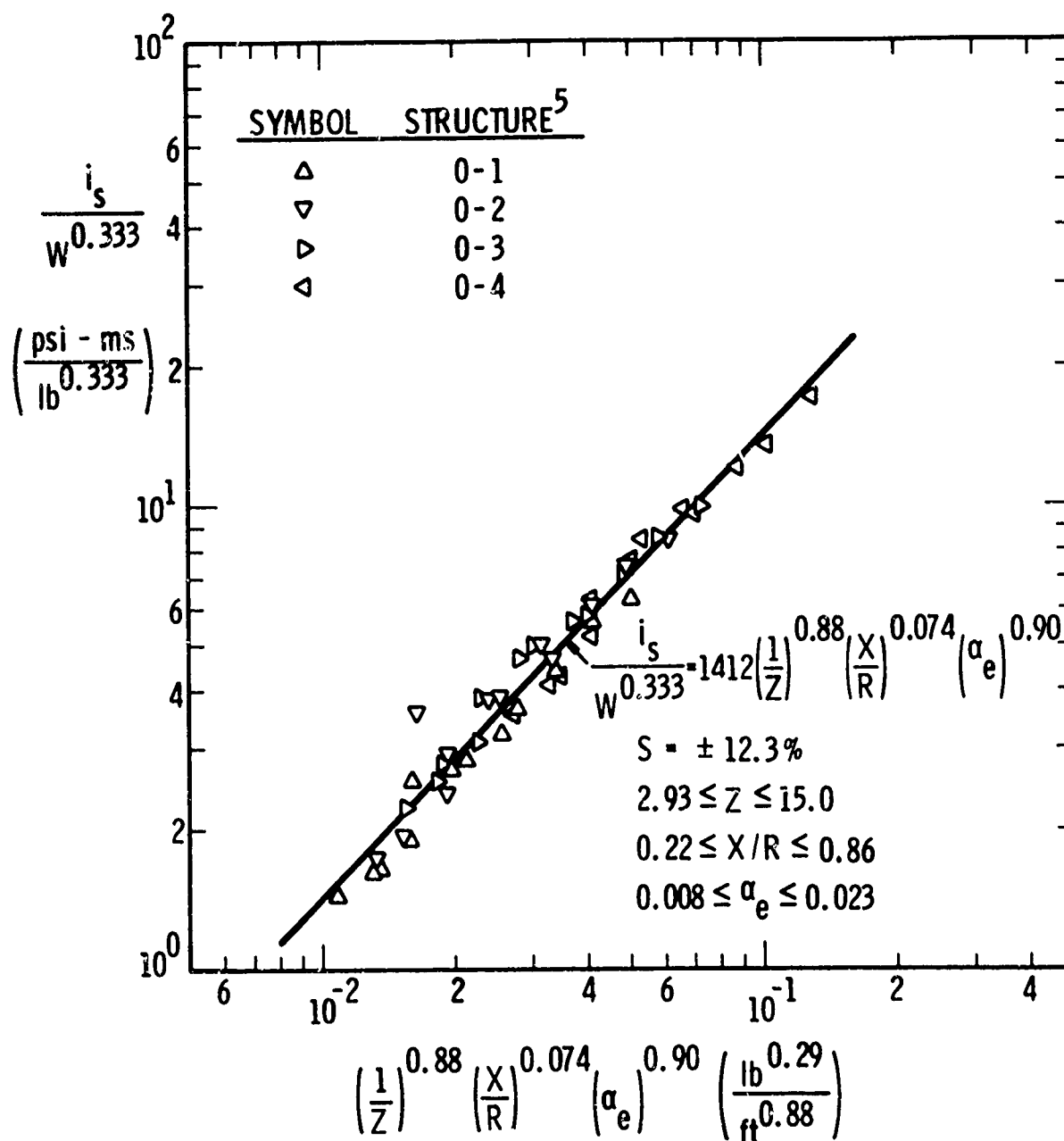


FIGURE 7. SCALED SIDE-ON IMPULSE OUTSIDE SUPPRESSIVE STRUCTURES WITH NESTED ANGLES AND PERFORATED PLATES

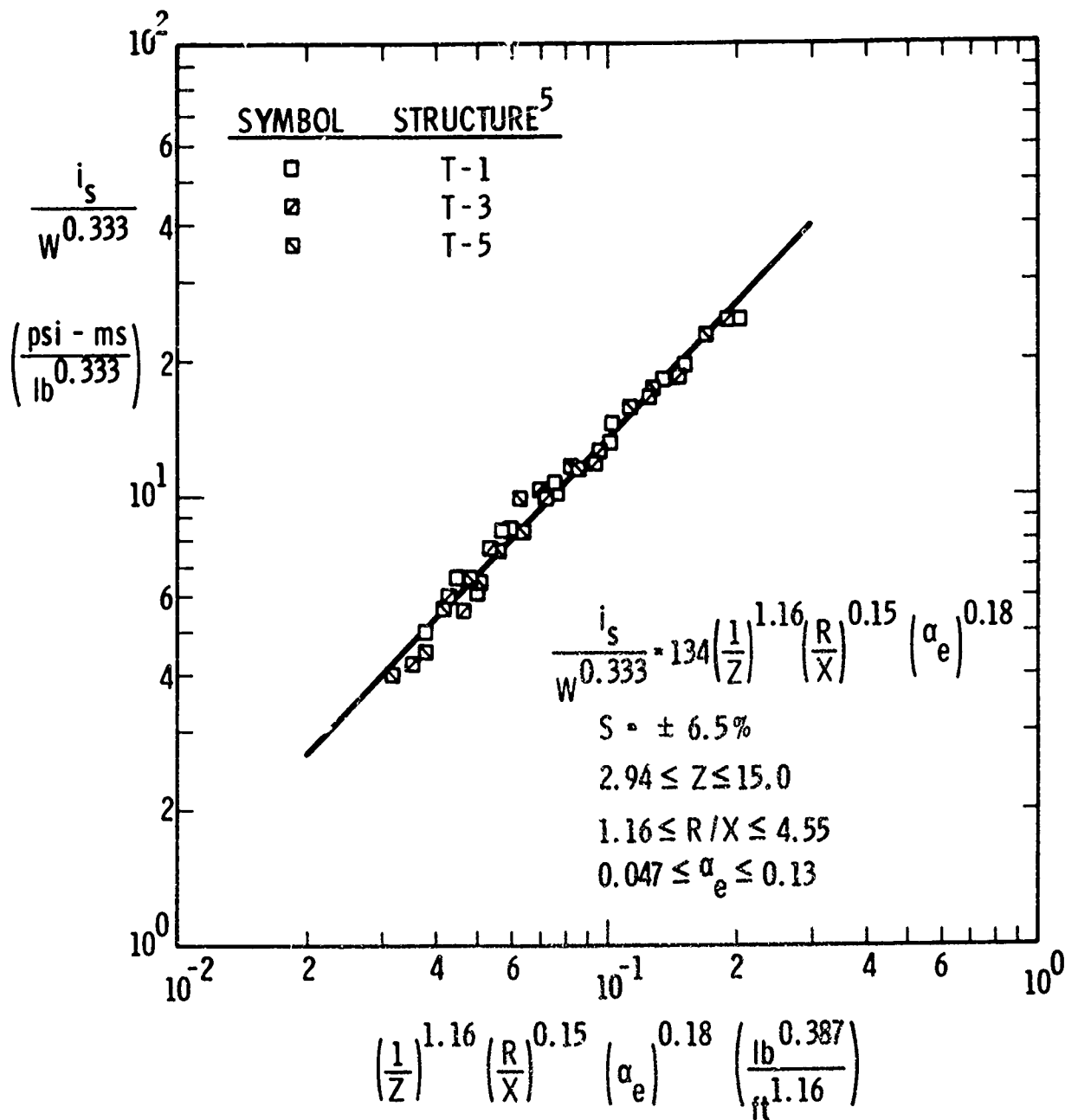


FIGURE 8 SCALED SIDE-ON IMPULSE OUTSIDE OF SUPPRESSIVE STRUCTURES WITH INTERLOCKING I-BEAMS

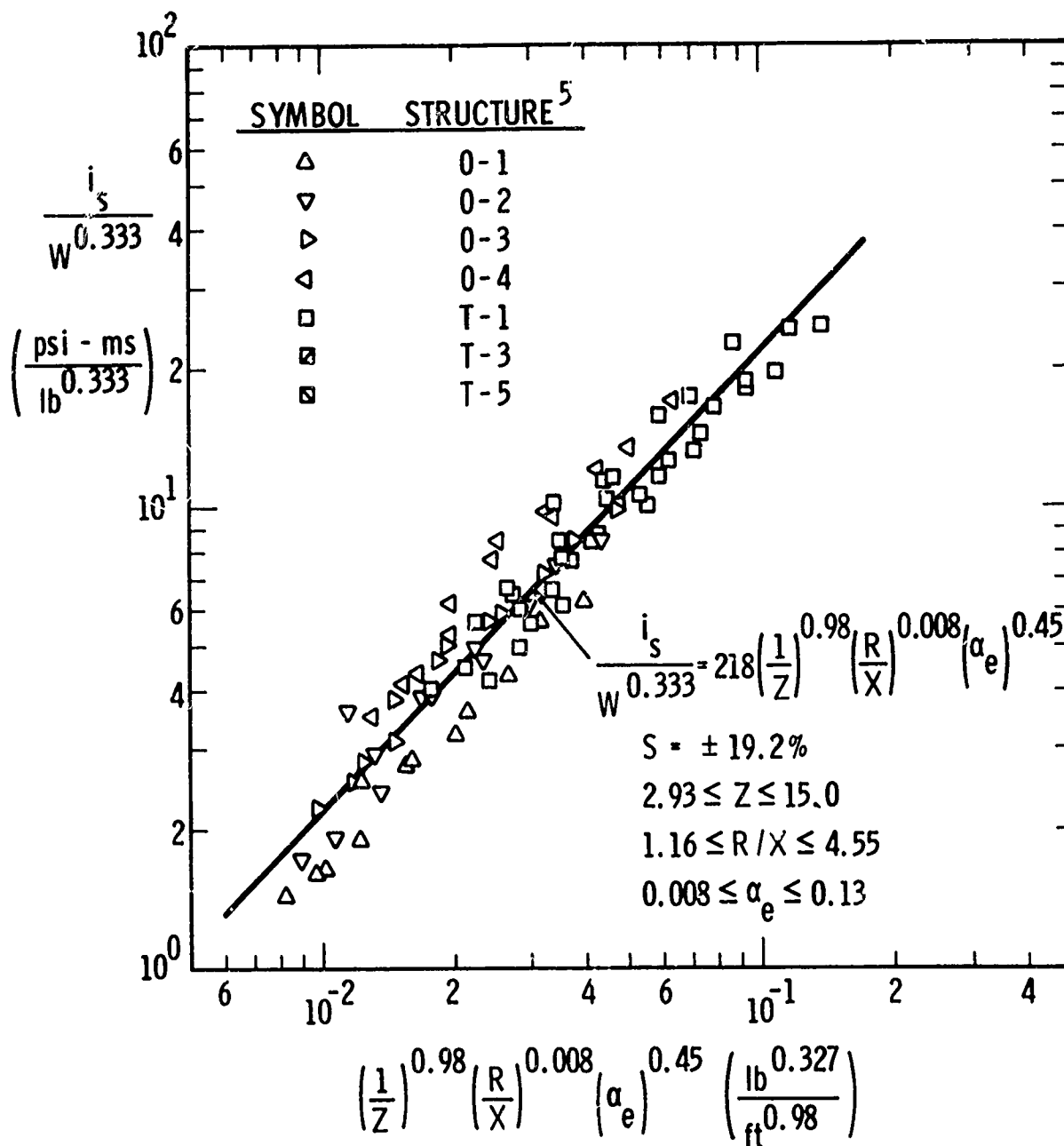


FIGURE 9. CURVE FIT TO SCALED SIDE-ON IMPULSE
OUTSIDE OF SUPPRESSIVE STRUCTURES

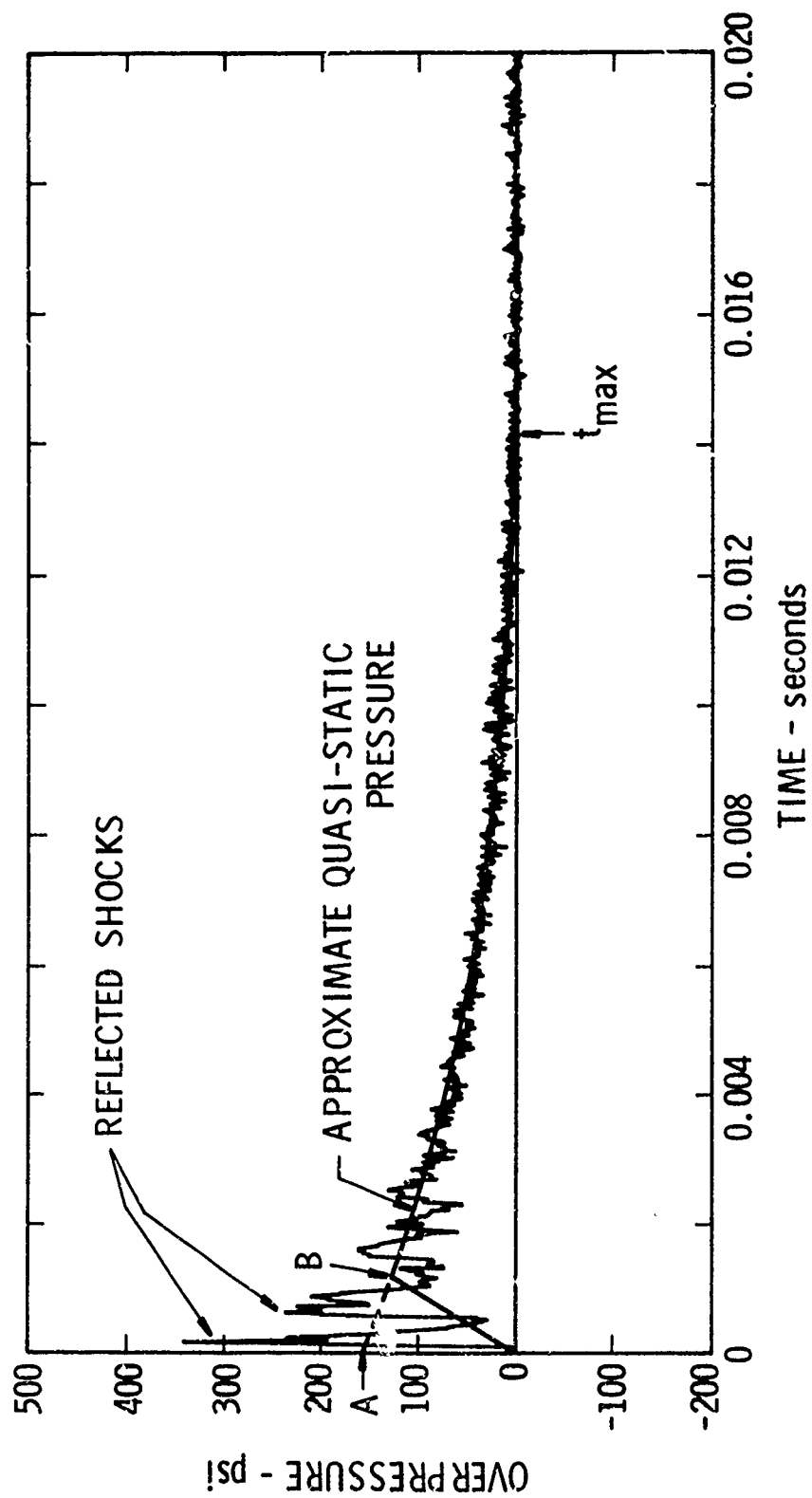


FIGURE 10. TYPICAL TIME HISTORY OF INTERNAL PRESSURE AT INNER SURFACE OF A SUPPRESSIVE STRUCTURE

of the surface, i.e., the innermost layer of the wall, and by the overall geometry of the structure. If the wall inner surfaces consist of relatively flat surfaces such as perforated plates or flanges of nested I-beams, the initial blast wave will reflect more or less normally from such surfaces. The reflected pressures and impulses can then be estimated with reasonable accuracy from tests of blast waves normally reflected from rigid, plane surfaces,^{2, 21, 22} or from sources of compiled data based on such tests.^{1 - 3} But, if the inner surfaces of the suppressive structure consist of geometries such as closely nested angle irons, the initial reflection process is much more complex, and measurement or prediction of the initial shock loading on such surfaces is quite difficult. An upper limit to the loading on each angle iron can perhaps be estimated by applying normally reflected pressures and impulses to the areas not shielded by adjacent angles. Curves of scaled reflected pressure P_r and impulse i_r are included here as Figure 11 for prediction of the initial shock loading. These curves are fitted to data for bare Pentolite spheres from References 1, 2, 21 and 22. To date, there are insufficient data on reflected pressure loads on actual suppressive structures to improve on curves such as these figures, although references such as Koger and McKown⁶ do give a few data points.

The initial and later reflected shock loads on the walls of suppressive structures are complicated not only by the character of their surfaces, but also by the overall structural geometry. Only for spherical chambers is the reflection process regular and easily predictable. But, rectangular box or cylindrical geometries are more practical shapes and are more adaptable to the vented panel designs common in suppressive structures. Complex reflections and reinforcements can occur in corners of such structures, and the implosion process after shock reflection is complex and irregular. Fortunately for one's ability to predict these loads, the latter shocks seem from data such as that in Reference 19 to be greatly attenuated compared to the first shock, so that ignoring reflected waves, or "smoothing" through the pressure-time traces, usually provides an acceptable approximate pressure loading.

B. Quasi-static Pressures

Prior to the suppressive structures program, several experimental studies were conducted to measure the maximum pressures and venting times for certain vented chambers. Weibull^{2, 3} reports maximum pressures for vented chambers of various shapes having single vents with a range of vent areas of $(A/V^{2/3}) \leq 0.0215$. These maximum quasi-static pressures are shown by Weibull to be independent of the vent area ratio, and to be a function of charge-to-volume ratio (W/V) up to 0.312 lb/ft³. He fitted a single straight line to his data, but Proctor and Filler⁷ later showed that fitting a curve to the data, with asymptotes to lines related to heat of combustion for small (W/V) and to heat of explosion with no afterburning for large (W/V), was more appropriate. Additional data on maximum quasi-static pressures and on venting times have been obtained by Keenan and Tancreto,⁸ and by Zilliacus, et al.⁹ Data from Reference 8 were used in Reference 4 to give predictions of maximum quasi-static pressures P_1 versus (W/V), and a scaled duration of this pressure versus scaled vent area ratio for initial design of suppressive structures. Concurrent with experimental work which preceded applications to suppressive structures, Proctor and Filler⁷ developed a theory for predicting time histories of quasi-static pressures in vented structures. Kinney and Sewell^{1, 4} did likewise, and

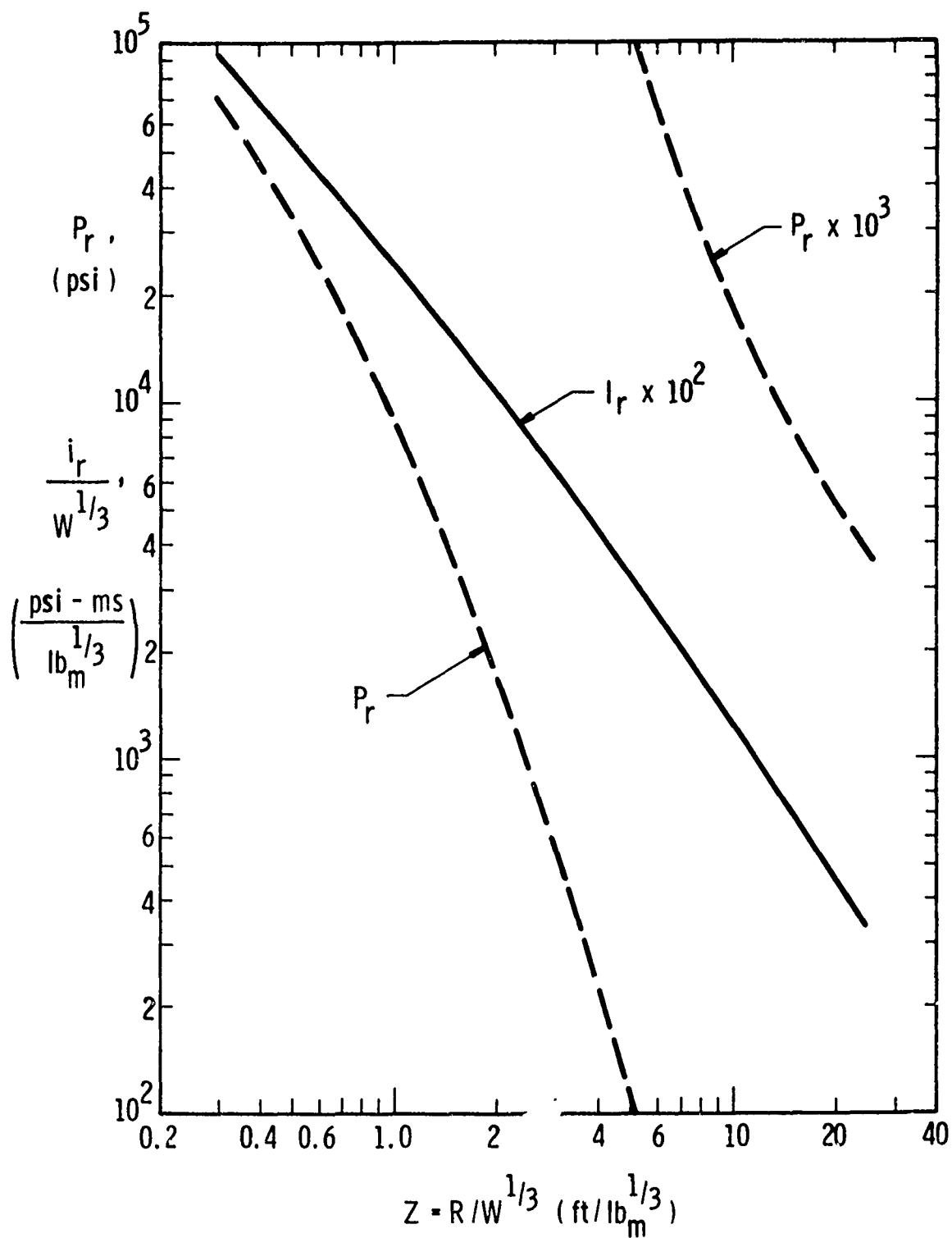


FIGURE 11. NORMALLY REFLECTED PEAK PRESSURES AND INPUTS FOR BARI, SPHERICAL PENTOLITE

also obtained an approximate formula for this time history. Converted to the scaled parameters discussed earlier, this equation is:

$$\ln \bar{P} = \ln \bar{P}_1 - 2.130\bar{\tau} \quad (11)$$

This equation gives a value for scaled venting time $\bar{\tau}$ of

$$\bar{\tau}_{max} = 0.4695 \ln \bar{P}_1 \quad (12)$$

The problem of blowdown from a vented chamber is also solved theoretically by Owczarek,^{12,13} given initial conditions in the chamber but assuming isentropic expansion through the vent area.

A few measurements were made of peak quasi-static pressures early in the suppressive structures program¹⁶ but only recently have sufficient additional data been recorded for this class of structure to add significantly to the measurements for other types of vented or unvented chambers. Reference 19 contains most of the suppressive structures venting data to date, supplemented by several measurements reported in Reference 6. In comparing such data with either previous data or theory, there are several questions raised by the general physics of the process and by the differences in venting through single openings in walls. Referring to Figure 10, one can see that the maximum quasi-static pressure is quite difficult to define because it is obscured by the initial shock and first few reflected shocks. Obviously, several reflections must occur before irreversible processes attenuate the shocks and convert their energy to quasi-static pressure. It therefore seems inappropriate to call point A in Figure 10 the peak quasi-static pressure, although this is the point used in Reference 19 to compare with code predictions from Proctor⁷ and the Sewell and Kinney equation [Equation (11)]. We have chosen to allow some time for establishing the maximum pressure, such as point B in Figure 10. For the records in Reference 19, this time was chosen to be 1 ms, which allowed at least two shock reflections. Koger and McKown⁶ employed a somewhat similar method to estimate peak quasi-static pressure.

Figure 10 also illustrates another problem inherent in reduction of vented pressure data, i.e., accurate determination of duration of this pressure. When the pressure traces approach ambient, the shock reflections have largely decayed. But, they approach the baseline nearly asymptotically, so that the duration is quite difficult to determine accurately. A possible duration t_{max} is shown in the figure.

As has been pointed out previously the definition of α_c for suppressive structures is not well defined. A possible definition of an α_c has been given earlier, but the specific value of this quantity for a given structure is not necessarily the same for venting and for external blast because the physical processes occur on much different time scales. Kingery, et al.,¹⁹ estimate α_c for blowdown by curve-fitting to calculations using Proctor's computer program.⁷ An example of their estimating is shown in Figure 12, indicating an α_c of 0.067 for this particular test and configuration. We found, however, that values of α_c which were adjusted to give good correlation with attenuation of blast pressures outside the structure also seemed

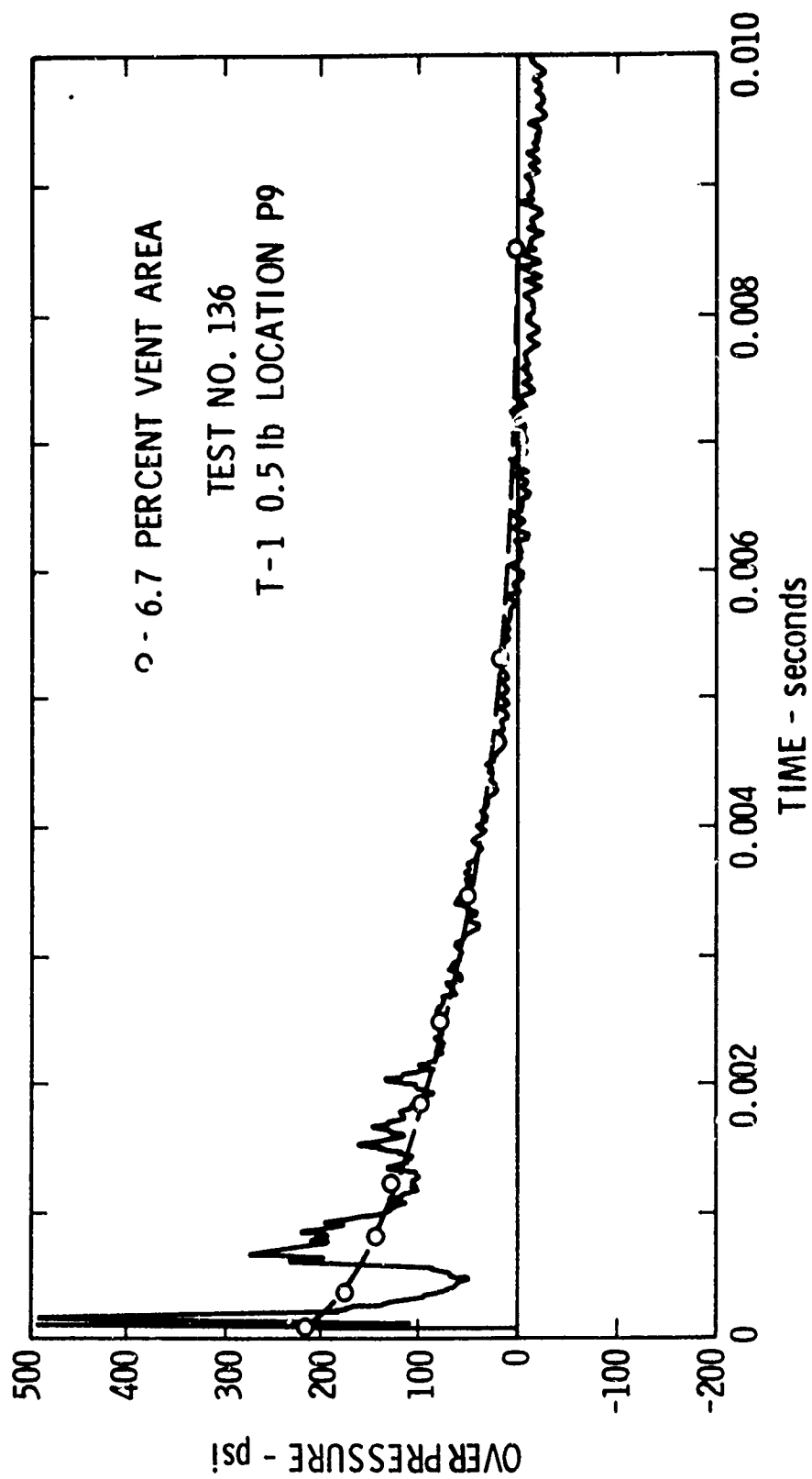


FIGURE 12. COMPARISON OF MEASURED DATA AND COMPUTER OUTPUT
FOR PROCTOR'S PROGRAM

to give reasonable correlations of data from Reference 19 with scaled venting times for curves from Reference 4.

For use in predicting maximum quasi-static pressures and venting times, we present two graphs. The first, Figure 13, is identical to the curve-fit of P_{\max} versus (W/V) originally made in Reference 4. Additional data points from References 6 and 19 have been added, but these are close enough to the original curve that no change seems warranted. The second plot in Figure 14 shows data from four references for scaled durations of vented pressures $\bar{\tau}_{\max}$ versus scaled absolute maximum pressure \bar{P}_1 . This form of scaled presentation is dimensionless and replaces the earlier dimensional one of Reference 4. It also allows predictions from theory to be compared with data. Sewell and Kinney's Equation (12) is plotted in this figure, as is a theoretical curve developed from Owczarek in Reference 12*. Data scatter is great enough that curve-fitting is difficult. But, Sewell and Kinney's equation seems to fit much better than the more sophisticated theory of Owczarek. We suggest using Equations (11) and (12) until more data become available. Note that the scatter in the data results at least partly from the fact that two measured quantities, maximum pressure and duration time, are plotted against each other, and thus the measurement errors are amplified.

C. Intrapanel Pressures

To properly design a suppressive structure to survive the blast loading, it has been necessary to estimate the loads due to gas pressure on the structural components of each layer of the walls. The flow makes a series of turns through varying areas and volumes to reach the lower pressure environment of the atmosphere. The pressure in these various compartments differs from the peak quasi-static pressure that is established in the initial compartment after the blast. Since no data presently exists for these intrapanel pressures, an analysis of the flow through the series of compartments has been conducted to estimate the pressure-time history in each compartment. Venting of a gas in a container through an opening has been investigated by other researchers.^{10,11} Kinney and Sewell¹¹ considered a confined volume of air that has been pressurized due to an internal explosion. The gas obeys the ideal equation of state from which the pressure rate is determined as

$$\dot{P} = (RT/MV)\dot{m} + (P/T)\dot{T} \quad (13)$$

where P is the absolute pressure, m the mass of gas retained in volume V , R the molar gas constant, M the formula mass, T the absolute temperature. The mass flow rate is given by:

$$\dot{m} = A\rho u \quad (14)$$

where ρ is the gas density, A is the cross-sectional vent area and u is the velocity of the escaping gas.

*Predictions of time histories of vented pressures are also given in Reference 12.

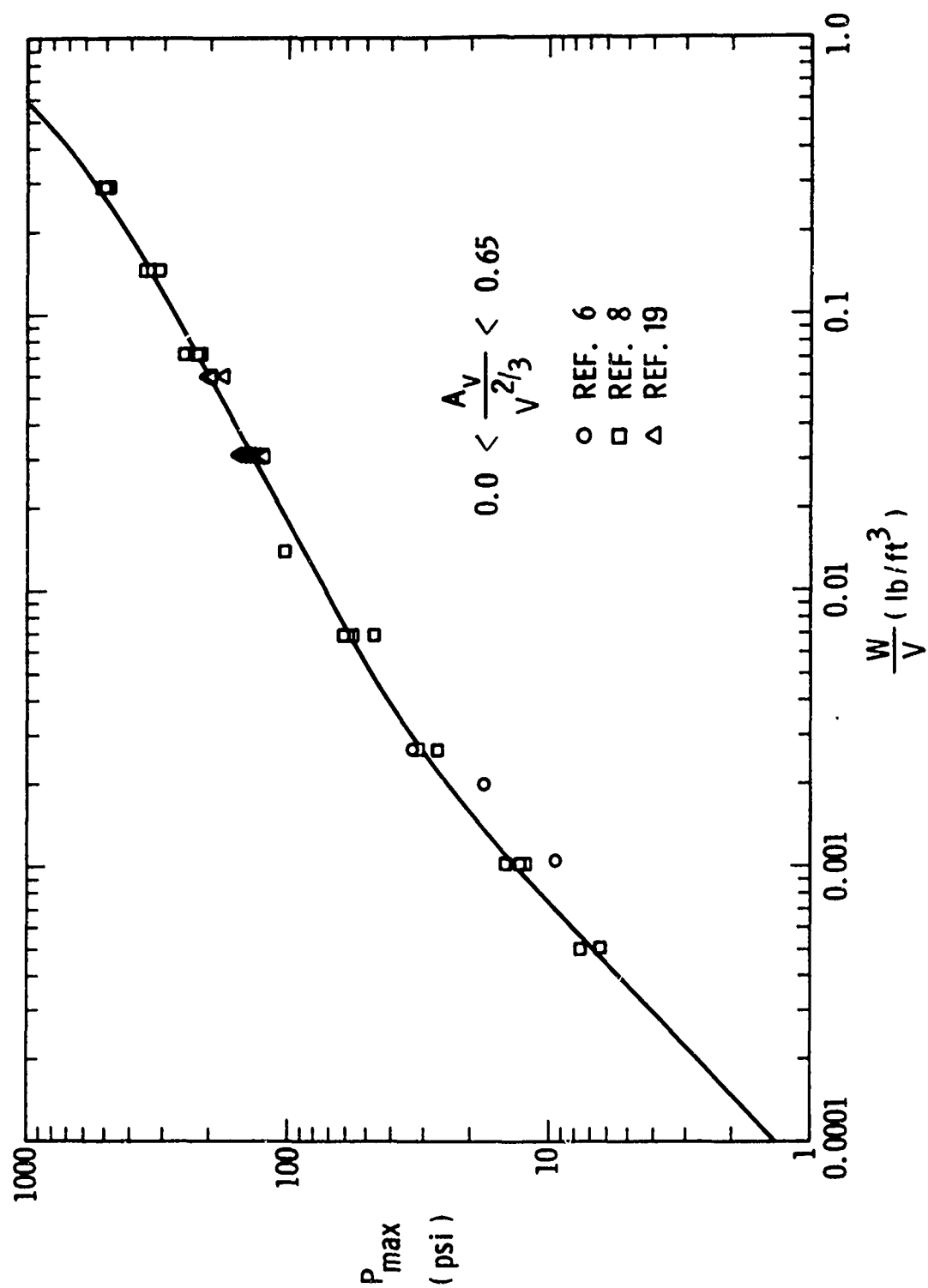


FIGURE 13. PEAK QUASI-STATIC PRESSURE IN PARTIALLY VENTED ENCLOSURES

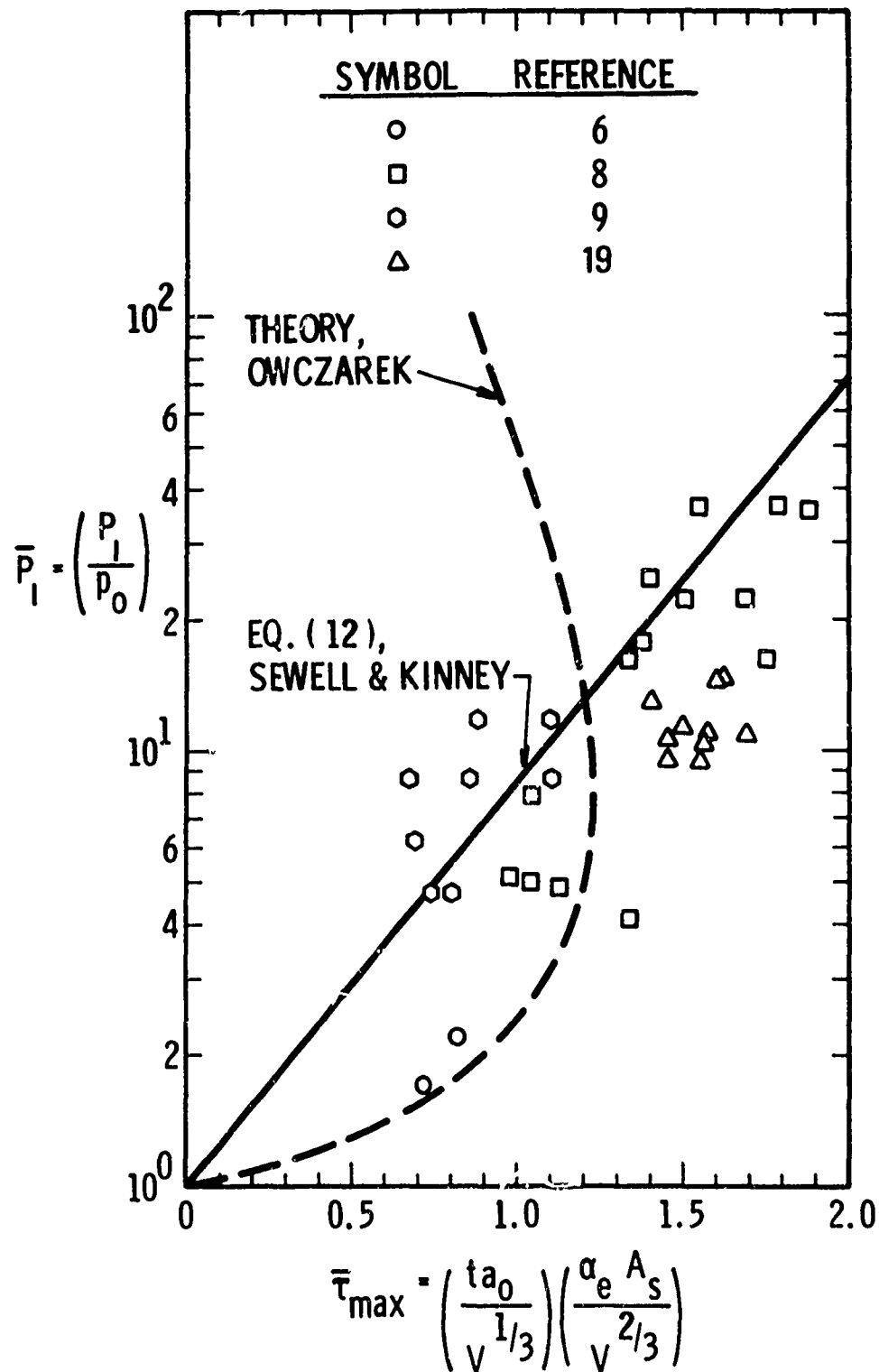


FIGURE 14. SCALED BLOWDOWN DURATION VERSUS SCALED MAXIMUM PRESSURE

The maximum attainable flow rate for a given upstream pressure is:

$$\dot{m} = C_D A P / (RT/M)^{1/2} [(2\gamma/\gamma + 1)^{1/2} (2/\gamma + 1)^{(1/\gamma - 1)}] \quad (15)$$

where γ is the ratio of specific heats and C_D is the discharge coefficient of the vent area.

The temperature rate \dot{T} which is due to the energy carried away by the vented stream and the heat transfer between the gas and the walls is given by:

$$\dot{T} = T(\gamma - 1) \dot{m}/m + [T(\gamma - 1)/PV] \dot{q} \quad (16)$$

where \dot{q} is the heat flow rate. In cases where the venting rate is very great, the heat transfer term can be neglected. These equations can be solved to give the pressure rate using a numerical procedure which Kinney and Sewell¹¹ outline in their report. The seemingly limiting assumption of this analysis is that the pressure rate can only be calculated down to the minimum overpressure required to give the maximum or sonic flow. Loads of importance may or may not occur below this pressure. Kinney and Sewell¹¹ have pointed out, however, that this analysis may be suitable below this minimum pressure due to experimental uncertainty at low overpressures and to the relatively small overpressures existing below this minimum.

The procedure for determining the pressure-time history of a single compartment with sonic flow as presented by Kinney and Sewell¹¹ was generally followed to develop a computer code (POOF1). POOF1 will compute the pressure time history of a multi-compartment system with sonic or subsonic flow.

Consider the following system (Figure 15) with given initial conditions, where volume V_1 is inside the suppressive structure and the remaining volumes represent the space between the walls.

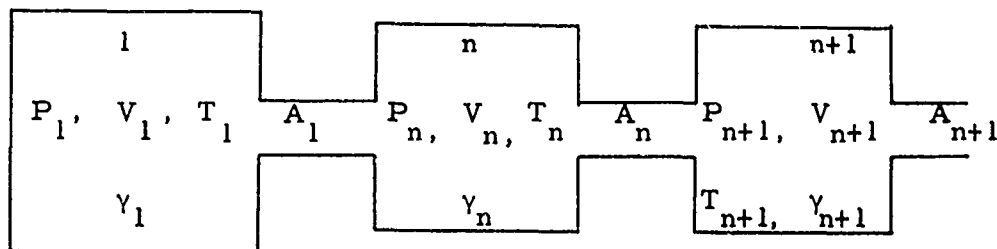


FIGURE 15. SCHEMATIC FOR VENTING CALCULATIONS

Assume that an explosion occurs in V_1 and heats the air in this volume causing quasi-static pressure rise. Also assume that the initial shock wave has blown through and that sonic flow exists through area A_1 . The mass flow rate out of the initial compartment can be calculated from Equation (15). Assuming that \dot{q} is negligible, the temperature rate and pressure rate can be determined from Equations (16) and (13), respectively.

The pressure P_n in the downstream compartments is dependent upon the change in the mass in the compartment due to the mass flow in \dot{m}_{n-1} and the mass flow out \dot{m}_n . This can be calculated using the equation of state coupled with a mass balance of the system,

$$P_n = RT_n(\Delta m_n + \dot{m}_n)/V \quad (17)$$

$$\Delta m_n = (\dot{m}_{n-1} - \dot{m}_n)\Delta t \quad (18)$$

where \dot{m}_{n-1} is known from the initial calculation. \dot{m}_n is dependent upon P_n , making it necessary to solve Equations (17) and (18) simultaneously for P_n after substitution of Equation (15) into Equation (18). The temperature change and resulting temperature for selected time increment in the n^{th} compartment can be calculated from the initial temperature and Equation (16) using \dot{m}_{n-1} . With P_n and T_n , m_n can be calculated. This procedure is used for all compartments downstream of the initial compartment. After a complete pass is made through the system of compartments, the pressure in the initial compartment at the next time increment is determined from the pressure rate. The procedure is then repeated until the quasi-static pressure goes to zero.

The input parameters required for P00F1 are the initial values of vent area, discharge coefficient, mass, volume, pressure, temperature, atmospheric pressure, specific heat ratio, gas constant and time increment for each compartment. The output of P00F1 lists the pressure as a function of time and also plots these results.

Predictions of pressure versus time using P00F1 have been compared to experimental data and to results using Proctor's code ¹⁰ and to the equation developed by Kinney and Sewell.¹¹ Generally, the total time for the overpressure to equal zero is 10-20% larger for the P00F1 predictions than for the other predictions. The difference is less when P00F1 is programmed to assume sonic flow exists throughout the venting process.

VI. DISCUSSION

Development programs are being supported by the U.S. Army's plant modernization program for the design and application of uniformly vented suppressive structures. These structures should provide better protection of personnel and facilities while reducing the safety distances from potential explosive hazards. In this paper we have presented scaling laws which apply to the blast waves that emanate from suppressive structures as well as to quasi-static pressure rise and decay from a detonation in a confined volume. Using external blast pressure data recently acquired we have updated earlier curve-fits for predicting peak side-on pressures from suppressive structures and free-field detonations. In the process we have empirically defined a method for computing relative vent areas for multi-layered, uniformly vented structures so that predictions of external pressures and the degree of reduction of these pressures can be made for a variety of wall configurations. Using experimental data from one-opening cubicles and suppressive structures a similar method for estimating effective vent areas is given which correlate with quasi-static pressure decay times.

Along with external side-on pressure predictive equations for specific structures and all types of suppressive structures for which data is available, predictive equations for side-on impulse have also been generated. Reflected pressure loading of the suppressive structures is discussed briefly and a summary graph is given for estimating the normally reflected peak pressures and impulses as a function of the scaled distance. For the quasi-static pressure load (which follows the reflected impulsive load when a detonation occurs in a relatively closed volume) graphs are also presented for estimating the maximum quasi-static pressure and venting times. Finally, the development of a computer code to estimate the intrapanel pressures caused by the internal quasi-static pressure is presented.

From the work reported in this paper, it is apparent that suppressive structures can be designed to significantly attenuate overpressures and impulses in blast waves which emanate from them, compared to explosions occurring in the open or in frangible structures. Specific applications for these structures can have quite different requirements for blast attenuation depending on factors such as the magnitude of the potential explosive hazard, proximity to adjacent structures or operations or whether personnel are normally allowed near the building or operation. For each application, allowable blast overpressures, or impulses, or both, can undoubtedly be established versus distance or at specific distances from the suppressive structure. As an example, the Category 1 structure discussed in some detail in References 4 and 24 was designed to attenuate the blast overpressure from 2500 lb of Comp B exploding in a melt kettle, to 50% or less of the free-field overpressure at the intraline distance for this quantity of explosive. This requirement then dictated the blast attenuation by the suppressive structure, and hence dictated much of the detail of the vent panel designs. Curves given in this paper would easily allow a choice of a different blast attenuation, for a number of vent panel configurations. For applications where the blast hazard is less severe, the required attenuation can perhaps be less and more "open" panel designs will result. This in turn will affect blowdown pressures and the structural design of the suppressive structure. The designer should, of course, realize that blast attenuation is only one aspect of suppressive structure design, with containment of fragments or attenuation of fireballs or firebrands often being equally important or overriding factors which must be considered.

This paper is in some respects a progress report on blast pressure studies in the suppressive structures program. Considerable related work is presently underway, with Edgewood Arsenal sponsorship. More test data are being obtained or evaluated for internal reflected pressures, blowdown pressures, and blast waves emanating from model or full-scale structures of several different configurations and panel designs. The experiments are being supported by or compared to predictions using gas dynamic or blast physics analyses or computer codes. Because of this ongoing work, some of the prediction curves or equations presented here may be somewhat modified, and will undoubtedly be supplemented by additional predictions for intrapanel pressures and other parameters which are at present ill defined.

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